STEERABLE PHASED ARRAY ANTENNA

The present invention relates to a steerable phased array antenna and more especially to a phase shifter for use in such an antenna.

Electronically steerable phased array antennas are known and generally comprise an array of antennas each of which has an associated phase shifter which produces a controllable phase shift in a beam transmitted by the array. A signal to be transmitted is split into a number of individual in-phase sub-signals, each of which passes through an individual phase shifter in which it is phase shifted before it is supplied to one of the antenna elements and transmitted therefrom. Transmission of all of the sub-signals produces an overall array output in the form of the beam. The beam can be steered electronically by carefully selecting the phase shifts which are applied to the sub-signals.

For microwave applications, the phase shifters are typically fabricated in Gallium Arsenide (GaAs). There are a number of problems associated with the use of such solid state components. Typically a phase array antenna has an array of several thousand radiating elements requiring a correspondingly large number of phase shifters. Since such phase shifters are expensive, this makes the entire array expensive. Furthermore, GaAs phase shifters are lossy, having a loss of typically -6 dB in the X band (8-12.4 GHz), and this leads to dissipation of power in the array. To compensate for these losses it is known to provide a gain element, typically one amplifier for each phase shifter. Even with this gain, it is only possible to compensate for relatively low power losses, typically 20-30 dBm before non linearities caused by power compression occur. In addition, high power levels can cause permanent damage to conventional phase-

shifters, so that ideally amplification should be provided downstream of the shifters.

Steerable phased array antennas are used to transmit radiation, particularly microwave radiation. In this context microwave radiation covers the range 0.247 GHz to 100GHz and includes the Ka band (26.5 GHz to 40 GHz) and the millimetric band (30 GHz to 100 GHz).

According to a first aspect of the invention there is provided a phase-shifter comprising: phase-altering means for introducing a phase shift into a signal whose phase is to be controlled and an actuator which changes shape in response to an electrical control signal, wherein the actuator is mechanically connected to the phase-altering means such that the change in shape of the former leads to a phase-altering action in the latter; characterised in that the actuator comprises a tubular stator of piezoelectric or magnetostrictive material, a piston coaxially disposed within the stator and a bearing member disposed between the stator and piston, wherein the stator distorts in an approximately frustro-conical manner in response to said control signal thereby causing the bearing member to roll axially along the stator, the movement of the bearing member in turn causing axial movement of the piston.

In a preferred embodiment the stator comprises a piezoelectric tubular member having electrodes on the inside and outside for coupling to a source of the control voltage and the bearing member comprises an elastically deformable and approximately annular in cross-section. Advantageously the stator has a slot extending completely through the wall of the tubular member and which describes a helical path about the tubular member.

In one embodiment the phase-altering means comprises a reflecting member inside a waveguide arrangement and attached to the piston, application of a control voltage to the stator electrodes causing the reflecting member to move, thereby altering a path length of a propagating signal. Preferably the waveguide arrangement comprises first and second parallel waveguides, the waveguide cavities communicating with each other over at least a part of their common length, the first waveguide containing a radiating element for producing radiation to be propagated along the first waveguide toward the reflecting member and the second waveguide having a radiating aperture, wherein, in use, radiation propagating in the first waveguide is reflected from the reflecting member into the second waveguide and out through the radiating aperture.

In an alternative embodiment the phase-altering means comprises a waveguide having one or more dielectric slabs of a first dielectric constant fixed to the waveguide and a movable dielectric slab of a second dielectric constant disposed in co-operating relationship with the one or more fixed slabs, the movable slab being connected to the piston. The one or more fixed slabs can be fixed to an inside surface of the waveguide and define a laterally substantially central cavity free from dielectric material, the movable slab being arranged to move axially within this central cavity. The waveguide is preferably attached to one end of the stator and movable slab to the piston by means of a push-rod. There is preferably a launcher provided in the waveguide wall at a location not occupied by the fixed or movable slabs, the launcher serving to generate a wave which passes through the slabs and out through a radiating aperture in the waveguide.

The piston can be hollow and the waveguide disposed in the piston. In this case the movable slab may be connected to the piston through connecting arms projecting radially inwardly from the piston and locating inside axially oriented slots provided in the waveguide wall and in one or more of the fixed dielectric slabs.

The first dielectric constant is preferably approximately equal to the second dielectric constant.

In yet a further embodiment the phase-altering means comprises a dielectric gel contained within a waveguide. Preferably the dielectric gel is contained within a bag, an outer surface of which is attached to an inner surface of a wall of the waveguide, and a transversely central end-portion of which is connected to the piston. The piston may be attached to the bag by way of a movable dielectric slab. Preferably the gel and slab have approximately the same dielectric constant.

According to a second aspect of the invention, there is provided a steerable phased array antenna comprising an input to supply a signal to the array, a splitter to split the signal into a plurality of sub-signals and a plurality of antenna elements to transmit the sub-signals, the antenna elements having associated phase-shifting means to phase-shift the sub-signals so that the array transmits the signal steered in a chosen direction, characterised in that each of the phase-shifting means comprises a phase-shifter in accordance with the first aspect of the invention.

In like manner, in a third aspect the steerable phased array antenna is configured as a

receiving array and comprises a plurality of receiving antenna elements having associated phase-shifting means to phase-shift the signals supplied by the antenna elements and a combiner connected to the phase-shifting means to combine the phase-shifted signals, characterised in that each of the phase-shifting means comprises a phase-shifter in accordance with the first aspect of the invention.

According to a fourth aspect of the invention, there is provided a tracking system incorporating a phased array antenna according to the second aspect of the invention.

Preferably the array transmits microwave radiation. Most preferably it transmits radiation in the Ka band.

Embodiments of the invention will now be described by way of example only with reference to the accompanying drawings in which:

Figures 1(a) and 1(b) show a schematic illustration of a phased array antenna system in accordance with the invention in a transmit mode and a receive mode, respectively;

Figure 2 shows an actuator as employed in a phase-shifting arrangement in accordance with the invention;

Figure 3 shows various shapes adopted by a component part of the actuator;

Figure 4 illustrates a first embodiment of a phase-shifter according to the invention in

two orthogonal views thereof;

Figures 5 and 6 are two orthogonal views of a second embodiment of a phase-shifter according to the invention in a first realisation thereof;

Figure 7 illustrates a second realisation of the second embodiment of a phase-shifter according to the invention in a general view;

Figure 8 is a cutaway view of the second realisation according to Figure 7;

Figure 9 is a cutaway view of the second realisation according to Figure 7 orthogonal to the view of Figure 8;

Figure 10 is the same view as Figure 9 but illustrating the displacement mechanism for the movable dielectric slab;

Figure 11 is a cutaway end-view of the second realisation according to Figure 7, and

Figure 12 shows a third embodiment of a phase-shifter according to the invention.

Figures 1a and 1b show a phased array antenna system in accordance with the invention, which is capable of full duplex operation. In Figure 1(a) a signal-processing unit 10 generates a normally sinusoidal signal of a given frequency which is amplified to a suitable level in a power amplifier 11, split as mentioned earlier in a splitter/combiner

12 into n sub-signals 13, these sub-signals 13 then being fed to respective phase-shifters 14 and thence to radiating elements 15.

In receive mode, the configuration is similar, except that individual low-noise amplifiers 16 are preferably provided for each sub-signal appearing at the output of the phase-shifters 14, rather than a single common amplifier at the combiner output 17. The apparatus 12 which operated in transmit mode as a splitter now operates in receive mode as a combiner.

This arrangement is used to transmit microwave radiation having a frequency of, typically, 30 GHz and thus a wavelength of 10 mm. In the following description the dimensions and parameters which are given relate to such a frequency, though it will be appreciated by those skilled in the art that the invention is not limited to this frequency of operation.

Figure 2 shows an actuator arrangement 20 comprising a tube 22, a bearing 24 and a piston 26. It can be seen that both the tube and the piston are elongate and so have an axial direction which is parallel to their central axes and a radial direction perpendicular to the axial direction.

The tube 22 comprises a single piece of piezoelectric ceramic material. The wall 28 of the tube has a slot 30 extending completely through its thickness which describes a helical path about the tube from one end to the other. Since piezoelectric ceramic material is hard, the tube 22 is most conveniently provided with the slot 30 while in its

green state before being fired. A suitable piezoelectric ceramic material is lead zirconate titanate (PZT).

The bearing is a resiliently deformable material, e.g. an elastomer, which may, in one realisation, have the shape of a toroid. If it is in the form of an O-ring having a circular cross-section, its thickness (in the radial direction) is arranged to be greater than the gap 32 between the piston and the tube. As a consequence, the bearing is stretched in the axial direction and squashed in the radial direction and in cross-section adopts a shape having two straight parallel sides and semi-circular ends, referred to as a "track" shape. The bearing is in contact with both the piston 24 and the internal surface of the tube and part of its effect is to centre the piston in the tube.

Instead of a toroid, the bearing may be substantially "track-shaped" to begin with and may also be hollow, the internal space being filled with a resiliently deformable material, e.g. a gas under pressure or a light oil.

The piston can comprise any material which is stiff in at least the radial direction and, if it is required to transmit displacement in an axial direction, as in most embodiments of the phase-shifter according to the present invention, it should be stiff in that direction also. It can even be hollow, which enables a piston to be provided having very low inertia. An example of a suitable low-mass material is expanded foam plastic.

The tube 22 is provided with electrodes 23, 25 on its external and internal curved surfaces, respectively, so that an electric field can be applied through the thickness of

the wall 28, thereby orientating dipoles in the material in a radial direction (that is, generally perpendicularly to the internal and external surfaces of the tube). In the configuration shown, both coatings are composed of a resistive material and contact rings 27, 29 and 31, 33 are made to bear against the ends of the outer and inner coatings, respectively. Rings 27 and 33 are connected together and likewise rings 29 and 31 and the resulting two connections form input terminals driven by a suitable power supply (not shown). The effect of this is to create voltage gradients along the axial length of the actuator tube, inside and outside the tube wall 28, the respective gradients being in opposite directions.

A similar effect can be created by employing low-resistance coatings, composed of, e.g., a metal such as silver or gold or a conducting PZT, splitting the helix halfway along its length and driving the now highly conductive coatings in antiphase by a suitable interconnection of end-connections of the coatings.

The application of the operating electric field in the manner described causes the shape of the tube to change from having a constant diameter along its length to having a flared or tapering shape extending from a relatively narrow end to a relatively wide end. This is due to the differently directed voltage gradients mentioned earlier. If an operating electric field having an opposite polarity is applied, the taper of the tube changes so that the end which was narrow becomes wide and vice-versa. Thus, switching an electric field from (a) a certain magnitude and polarity to (b) zero magnitude and thence to (c) an equal magnitude and opposite polarity to that in (a) will produce the shapes shown in Figures 3(a), 3(b) and 3(c), respectively (shown exaggerated for clarity). The degree

of shape change depends on the magnitude of the operating electric field applied.

The tube deformation just described forces the piston up and down the tube in a manner shortly to be explained.

The degree of change of shape, and hence of movement, of the piston can be enhanced by careful choice of the structure of the wall of the tube 22. Compared to a single and integral piece of one ceramic such as PZT, greater movement for the same applied voltage can be obtained by giving the wall a multilayer structure, in which a plurality of piezoelectric layers are provided, each having their own electrodes. Alternatively, lower driving voltages can be used to produce the same movement.

Alternative enhanced wall structures include a unimorph bender, in which the ceramic tube is bonded onto or inside a metal liner, and a bimorph bender, in which the tube comprises two piezoelectric tubes bonded together one inside the other, the tubes being poled in opposite, preferably radial, directions. In both unimorph and bimorph benders the enhanced movement is due to differential expansion occurring during operation.

The use of PZT may provide, for example, a 10 mm displacement of the piston in a response time of 25 ms. This may be under an operating voltage of 150 V for a tube wall thickness of 21mm, although lower voltages could be used if a multi-layer tube was provided having thinner individual layers of piezoelectric material. Other wall structures can be used, as has already been mentioned.

As an operating electric field is applied to the tube, the internal diameter of the tube decreases at one end and increases at the other and this causes a "rolling" motion of the bearing which forces the piston toward the wider end of the tube. More precisely, points of mutual contact between the bearing and wall on the one hand and between the bearing and piston on the other do not move relative to each other except at the ends of the bearing where the bearing material rolls away from/onto its respective contact surface. Thus, in these end-regions, parts of the surface of the bearing either move into contact with the piston or move out of contact with it and a similar effect occurs between the surface of the bearing and the tube. The rolling action just described does not involve sliding friction, rather the presence of static friction prevents relative motion of the bearing and wall and of the bearing and piston.

It will be understood that, being-based on a simple mechanical arrangement, the actuators themselves are relatively inexpensive and allow a relatively inexpensive steerable phased array to be produced by means of them in accordance with the invention.

In producing a steerable phased array it is necessary for phase shifts of different values to be applied to the subsignal radiation being transmitted by the individual radiating elements in order that a beam may be steered. At most, a relative phase shift of one wavelength is required between antennas in the array. This means that, for transmitted radiation having a wavelength of 10 mm, a maximum relative wavelength shift of 10 mm is required.

The actuator arrangement 20 can induce a phase shift in transmitted radiation in a number of ways. In a first embodiment, illustrated in Figure 4, the actuator has a reflector 34 attached both to the piston 26 and to a cavity-separator extension piece 36 which extends axially of the reflector 34 and comprises a separating section 42 proper and an aperture section 44 disposed between the separating section 42 and the reflector 34. A pair of waveguide sections 38, 40 having parallel longitudinal axes are divided one from the other by, firstly, a fixed separator member 46 and, secondly, the cavity-separator separating section 42. One waveguide section 40 is provided with a radiating element 48 at its distal end and the other waveguide section 38 has a radiating aperture 50 at its distal end. The proximal ends of both waveguide sections are attached in common to the wall 28 of the actuator arrangement 20.

The mode of operation of this embodiment is as follows. A signal is radiated from the radiating element 48 and propagates down the waveguide section 40 towards the reflector 34 which reflects it through the aperture 44 in the cavity separator 36 into the adjacent waveguide section 38. When in the waveguide section 38, the signal is guided toward the radiating aperture 50. By moving the reflector by means of the PZT actuator arrangement 20, the path length between the radiating element 48 and the radiating aperture 50 is varied by an incremental amount, thereby modifying the phase of the signal leaving the radiating aperture 50. The reflector 34 and cavity separator 36 are moved linearly in the waveguide sections by the piston 36 that is moved by the squeezing action of the actuator.

In a second embodiment (see Figures 5 and 6) a single waveguide 54, which is likewise

attached to the wall 28 of the actuator 20 at one end thereof, contains two fixed dielectric slabs 56 attached to opposite inside walls of the waveguide and a movable dielectric slab 58 attached by a rod 60 to the piston 26. The dielectric constant of the movable slab is approximately the same as that of the fixed slabs. The waveguide is provided with a launcher 62 which is received through an opening 64 in a side wall of the waveguide.

In operation, a signal is radiated from the launcher into the waveguide cavity. The signal propagates along the waveguide towards the fixed and movable dielectric slabs 56, 58 which modify the wavelength of the signal in proportion to the length of the overlap between the moving and fixed dielectric slabs. More precisely, the phase-shift in the radiated signal is expressed as:

$$\Delta\phi = \{(\beta_1 + \beta_3) - (\beta_2 + \beta_4)\} \times x$$

where x = displacement of the movable slab from its fully overlapping position and βn = propagation constant as seen by the wave as it travels from the launcher outwards. Looking at Figure 5, β_1 applies between the bottommost part of the fixed slabs 56 and the bottommost part of the movable slab 58; β_2 applies between the bottommost part of the movable slab and the topmost part of the fixed slabs; β_3 applies between the topmost part of the fixed slabs and the topmost part of the movable slab, and β_4 applies beyond that.

A variation of this embodiment is illustrated in Figures 7-11. In this variant realisation the mode of operation is exactly the same, but the construction is different. Instead of the movable dielectric slab being coupled to the piston by means of a push rod 60

(Figures 5 and 6), it is directly attached to the piston through connecting arms 70. The connecting arms 70 pass through slots 71 in the waveguide 72 and fixed dielectric slabs 74 and are attached to the movable slab 76 at an intermediate point thereof along its length. Thus in this realisation the actuator surrounds part of the waveguide 72 rather than being at one end of it, as in the Figure 5/6 realisation. As in the first realisation, though, the waveguide is secured to the actuator stator.

Figures 9 and 10 are views of Figure 8 from the side, like features being designated by like reference numerals. Figure 10 shows the slot 71 in the waveguide and fixed dielectric slabs 74 and a connecting arm 70 in section which, in practice, connects the piston 73 and the movable slab 76. Either one slot only may be provided on one side of the waveguide and involving only one fixed slab, or two slots may be provided on opposite sides. The latter, balanced, arrangement is preferred for mechanical reasons. Figure 11 is a cutaway underside end-view of the second realisation of the second embodiment and shows the actuator wall 28, the bearing 24, the piston 73, the waveguide 72, the launcher 62 and, inside the waveguide, the fixed slabs 74 and movable slab 76. The slot 71 made in the waveguide wall and in the fixed slabs 74 is also shown.

In a third, alternative, embodiment shown in Figure 12 the piston 26 is used to drive, through a connecting rod 60, a movable dielectric slab 76 which is attached at its ends 82, 84 to a deformable bag 80 filled with a dielectric gel 86. The slab and gel both ideally have approximately the same dielectric constant. The bag 80 is secured on its outer face to inner, opposite wall-faces of the waveguide 54. In operation the piston

moves the rod 60, which displaces the movable dielectric slab 76, which, in turn, imposes a distortion in the shape of the bag 80. The effect is similar to that of the fixed/movable slab embodiment, wherein a change in the path length of the propagated signal associated with a particular propagation constant causes a phase-shift in that signal.

In all these embodiments and realisations the displacement of the piston needs to be in the region of one wavelength, that is about 10 mm for a 30 Ghz signal, to produce a phase-shift equal to one wavelength.

It should be noted that the helically slotted piezoelectric tube provides for large displacement in relation to its size. For an arrangement in which the bearing is located at one end of the tube and is displaceable to the other end of the tube, the maximum possible displacement of the piston is the length of the tube. Of course, if the piston is located more towards the mid-point of the tube, the displacement would be less. This latter configuration provides a convenient way of achieving a type of "centre-zero" arrangement whereby in the piston's rest position (mid-position) the phase-shifter corresponds to zero phase shift, but when the piston is driven to one side or other of its mid-position there is a positive or negative phase shift, respectively.

By creating an array of independently controllable actuators/phase-shifters to form a suitable aperture, it is possible to steer a transmitted signal in space by varying the displacement of the actuator pistons relative to each other. In an embodiment operating at 30 GHz having a hexagonal aperture of 0.5 m and a square array having an element

spacing of half a wavelength, 7700 individual antennas are required. With a microwave reflector as described in the first embodiment (Figure 4) the rate of change of phase-shift $\delta\theta/\delta t$ of each element is about 28 deg ms^{-1}. With a dielectric-filled waveguide this rate of change is influenced by the phase velocity of the radiation within the dielectric medium, as well as by the velocity of the dielectric piston. Assuming that the actuators can induce a relative phase shift of up to 360° between particular antennas, the array can track at least ±45° from boresight.

In order to ensure that grating lobes are not generated in "visible" space, the lateral spacing of the radiating elements in the array should be approximately half a wavelength, i.e. about 5 mm for radiation having a frequency of 30 GHz..

A significant benefit of the invention is that it enables phase shifting to be incorporated into the antenna. Indeed, it may be conveniently arranged for the end of the waveguide through which the radiation is exiting to constitute the radiating antenna itself, so that no additional discrete antenna element is required. Thus in this realisation the radiating aperture may be considered to constitute the actual antenna element. Alternatively, the waveguide may be coupled to its own discrete antenna element (not shown). The result is a low-cost phased array system compared with conventional systems which traditionally use large quantities of expensive active microwave components or a likewise costly complex mechanical arrangement. By incorporating phase-shifting into the antenna, a whole array can be fed directly from a single manifold, as illustrated in Figures 1(a) and 1(b) (see splitter/combiner 12). Furthermore, since the various phase-shifters described are able to withstand large amounts of RF power without damage, the

manifold may be preceded by just a single high power microwave amplifier 11.

Although the array has a relatively fast response time, it is not as fast as pure solid state electronically scanned arrays. Nevertheless, the scanning rate of these arrays is certainly fast enough to be used as an antenna arrangement in satellite tracking. It is also fast enough to be used in numerous communications applications where switching of a transmitting or receiving direction is required, such as OTM (on the move) Communications for HMMWV (high-mobility multi-wheeled vehicle) and UAV (unmanned airborne vehicles).